Thermal Management - a key technology for the success of e-mobility

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ABSTRACT

Thermal management in vehicles continues to play a significant role in enabling technologies to meet the constant and more stringent demands of energy efficiency and CO2 emissions.

To meet the most stringent emission levels, we see a transition of propulsion technology from internal combustion engines to electric motors. In both, the thermal management of the components is of great importance for the durability and for the enabling of the optimal operating conditions in the system.

In battery electric vehicles (BEV), the complexity and the demand for an efficient use management of the available energy in the vehicle increases. The abundant heat energy of combustion engines is no longer available in BEVs, and the energy accumulated in batteries needs to be optimally used for the various needs of the vehicle.

This paper presents thermal management solutions that support this transition, presenting technologies and configurations of thermal circuits that enhance the mileage of vehicles, the battery functionality, and the modularization of systems. Comparative solutions options with benchmark of some BEVs vehicles tested in wind tunnel will also be presented.

INTRODUCTION

The automotive industry is accelerating the electrification of the vehicles due to more stringent emission legislations.

Current legislation and OEM announcements lead to further increasing electrification globally. In 2022, 15,9 million electric cars were produced, representing 19,3% of total produced vehicles globally. It´s an exponential growth compared to previous years where this share was 13,2% in 2021, and 6,4% in 2020. The global future scenario shows that the share of EV´s in 2030 will be 55%, and it increases to 70% in 2035. (Figure 1) The growth is basically lead by Europe, North America and China [1].

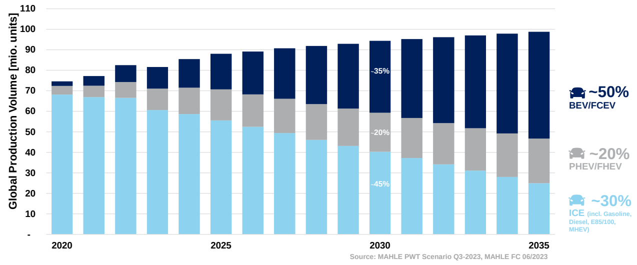

Figure 1. Global Powertrain Production Scenario until 2035 [1]

This increase in the electrification of the powertrain brings new challenges for the development on most of the vehicle components.

For the traditional internal combustion engine, the availability of heat energy in the vehicle is plenty, and the main function of the radiator is to release the excessive heat to the ambient and avoid overheat of the engine parts. Part of this ‘free’ heat energy is also used for the passenger cabin heating using a coolant heat exchanger located inside the cabin air conditioning unit.

In the other hand, when it comes to a full electric vehicle, the energy available is mainly coming from the batteries. Primarily, this is the only energy source the vehicle has for the drivetrain, cabin comfort (cooling and heating) and to feed all its on-board accessories.

Therefore, an intelligent and efficient vehicle thermal management is extremely important for the success of electric vehicles.

There are 3 main critical factors for the success of the electrical vehicles:

- Driving range optimization
- Fast battery charging time
- Components complexity and cost

This paper presents thermal management solutions proposals for above challenges, supporting in this way the technical feasibility and acceptance of electrical vehicles.

ENERGY MANAGEMENT ON ELECTRIC VEHICLES

The main difference between internal combustion engine (ICE) vehicles and electric vehicle (EV) is the source of energy the vehicle uses to power the engine and drive the wheels. ICE vehicles use the energy of fuel combustion to move pistons, and thus, to drive the vehicle. Whereas EV vehicles have the battery as a source of energy and an electric motor to drive the vehicle.

Despite the battery development has improved significantly in the last years concerning the increase in the power density, the driving range of ICE vehicle is, still, superior. The optimization of the available energy source therefore is of upmost importance on EVs platforms, and an intelligent thermal management can help significantly to improve the driving range.

HEAT PUMP HEATER SYSTEMS – The use of heat pump systems in EVs is an efficient solution to optimally use the energies of the vehicle to heat the passenger cabin.

In a traditional ICE vehicle, most of the heat generated in the combustion engine is dissipated to the ambient air by a radiator, and a part of this energy is used to heat the cabin by a heat exchanger – heater core - inside the air conditioning housing (Figure 2). In this case, availability of the heat energy is not a problem since most of this energy is anyway dissipated and wasted to the ambient air, and there is no impact on vehicle driving range.

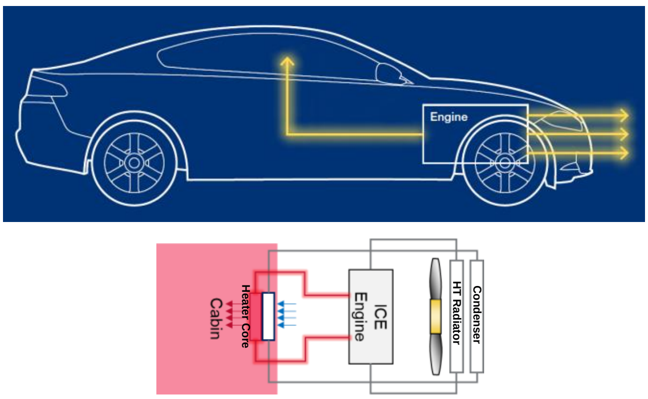

Figure 2. Cabin Heating in ICE Vehicle

The first solutions on cabin heating of EVs are based on high voltage electric heater to warm the cabin. The problem of this solution is that the same accumulated energy in the batteries to drive the vehicle would also be used for cabin heating, bringing a considerable reduction on the driving range. Moreover, the heat generated by the electric motor and power electronics are dissipated to the ambient with no recovering, wasting an important portion of energy that could have been reused. (Figure 3)

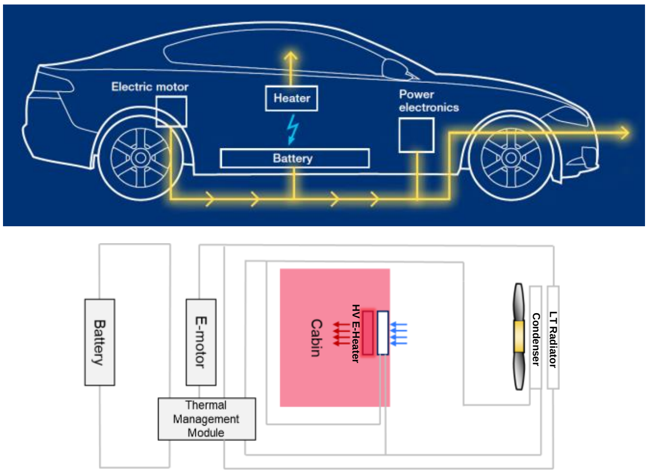

Figure 3. Cabin Heating in EV Vehicle with High Voltage Electrical Heater

A heat pump system is based on using heat absorbed from the ambient air, the electrical powertrain and electronics waste heat energy. This reduces the energy requirement of the cabin heating from the battery, improving the driving range mileage. (Figure 4)

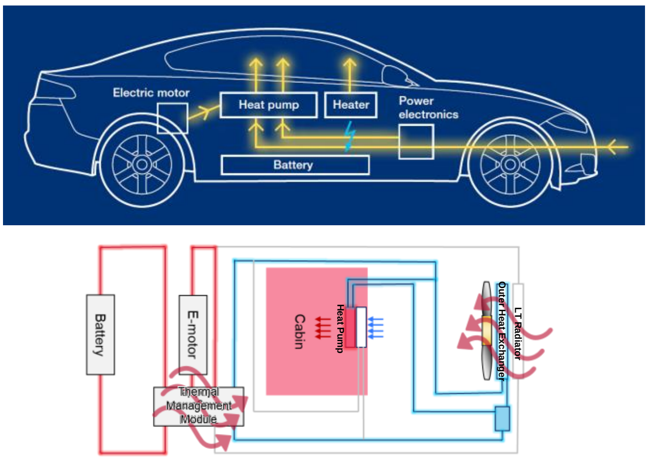

Figure 4. Cabin Heating in EV Vehicle with Heat Pump

Specially in winter times, where the cabin heating is more demanding, the impact and benefit of the heat pump system in the driving range improvement can be most seen.

Tests comparisons at 0ºC ambient temperature driving showed that vehicles equipped with heat pump systems significantly improved the driving range, compared to the high voltage (HV) electrical heater solutions [2]. The biggest differences can be seen in the compact vehicles, where the installed battery capacity is smaller, in the example 20kWh, and any energy demand make a significant impact on the vehicle driving range. Considering 100% the range of vehicle with no heating at all, the use of HV electric heater reduces the driving range to 60%, and the heat pump system reduces to 83%. The bigger the battery is, less impact can be seen in the driving range reduction. For a mid-size vehicle equipped with an 80kWh battery, the HV electric heater solution reduces the driving range to 79%, and the heat pump system to 92%. For a medium duty truck with a 200kWh battery, the reductions on driving range are respectively reduced to 90% and to 97%. (Figure 5)

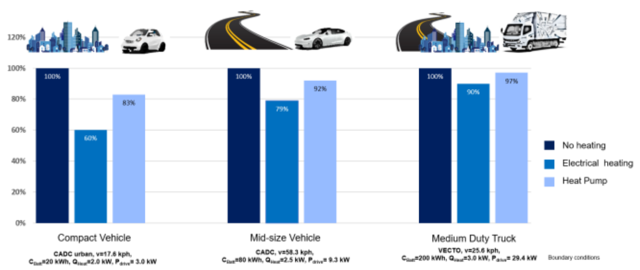

Figure 5. Driving Range Comparison at 0º C of Heating Systems [2][3]

Direct and Indirect Heat Pump Solutions– The heat pump circuits can have direct or indirect system configurations.

In the direct system configuration, the heat energy to warm the passenger cabin is rejected directly by the refrigerant gas, through a heat pump heater (HPH) that transfers the heat from the refrigerant to the incoming air of the cabin. (Figure 6)

The indirect system dissipates heat to the cabin using hot coolant by a heater core (HC). The coolant receives heat from the indirect condenser (iCond). The iCond is a refrigerant-coolant heat exchanger. This system is less efficient due to the heat losses that happen in the coolant circuit. (Figure 7)

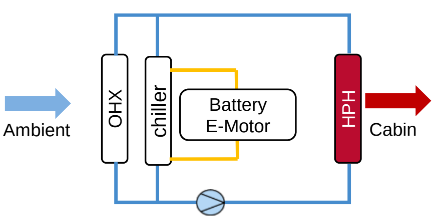

Figure 6. Heat Pump Direct System

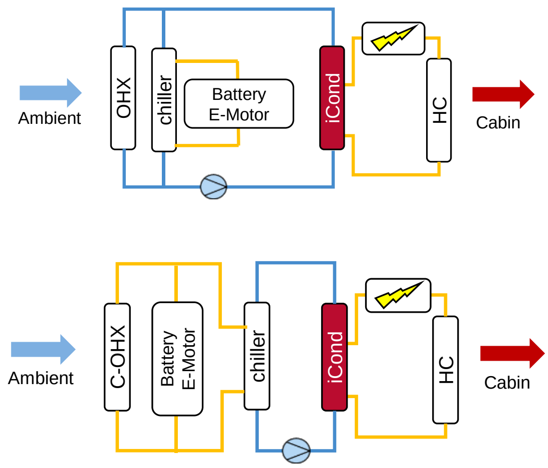

Figure 7. Heat Pump Indirect Systems

A standard A/C system causes significant driving range reductions in moderate and low ambient temperature conditions due to the high energy consumed by electrical heater and electrical compressor. It was already seen in the previous paragraphs that heat pump systems enable driving range optimization. In an internal comparison measurement (Figure 8) we can see the impact on BEV driving range of the direct and indirect systems. Direct heat pump systems show less driving range reduction than indirect systems due to the direct heat recovery and direct rejection to the cabin. The indirect systems are less efficient due to heat losses in the coolant heating loop. These losses are shown in the graph to be more significant below the 0ºC ambient temperature. [2]

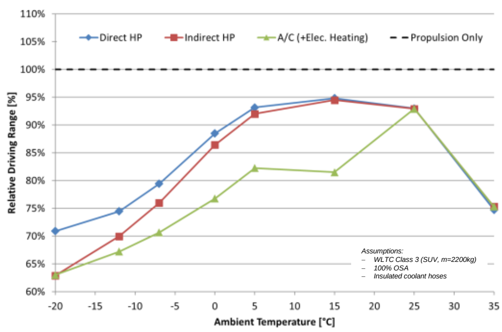

Figure 8. Impact of cabin conditioning on EV driving range [2][3]

As a proposal of a highly integrated and efficient BEV thermal management system, the Direct Thermal System (DTS) solution is presented.

It´s a direct heat pump system, with heat energy absorption from ① ambient air, ② electric power train, ③ electronics, and ④ battery, that will be used to heat the passenger cabin. The heat energies ②③④ are collected by the ⑤ Chiller, and the heat energy from the ambient is collected by the ⑥ OHX (Outer Heat Exchanger). During the cabin heating mode, the gas refrigerant that absorbed the heat energies (①②③④) is compressed by the ⑦ electrical compressor to the ⑧ heat pump heater located inside the air conditioning module to warm the passenger cabin. (Figure 9)

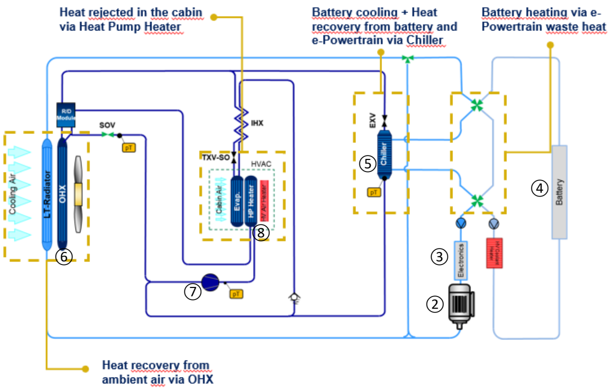

Figure 9. Direct Thermal System circuit configuration [MAHLE]

Test comparisons were performed internally at MAHLE with some state-of-the-art BEV vehicles from market and the vehicle installed with a DTS configuration solution. (Figure 10) The baseline vehicle does not have the heat pump system installed, i.e., the cabin heating is given by a HV electrical heater. For the comparison, the electrical power consumption of the vehicles was measured and compared. The vehicles with the heat pump system, as expected, had a significant reduction on the electrical consumption of the vehicle, which explains the improvements on the driving range reduction if compared to a purely electrically heated cabin solution. The comparison between 'Maker A without HeatPump' and 'Maker B' vehicles shows that the series heat pump system reduced the power consumption by 1.69 kWh/100km (29% savings) against a pure electrical heating solution. Compared to 'Model B', the 'Model B face lift' series heat pump system reduced the power consumption by 0.61 kWh/100 km (15% savings). Compared to 'Model B face lift', the 'Maker A' series heat pump system reduced the power consumption by 0.07 kWh/100 km (2% savings). And lastly, compared to the 'Maker A', the 'M DTS' heat pump system has an advantage concerning energy consumption of 0.70 kWh/100 km (DTS saves another 20%). If we compare to the baseline 'Maker A without HeatPump' solution, the DTS solution shows more than 50% saving on the energy consumption [2].

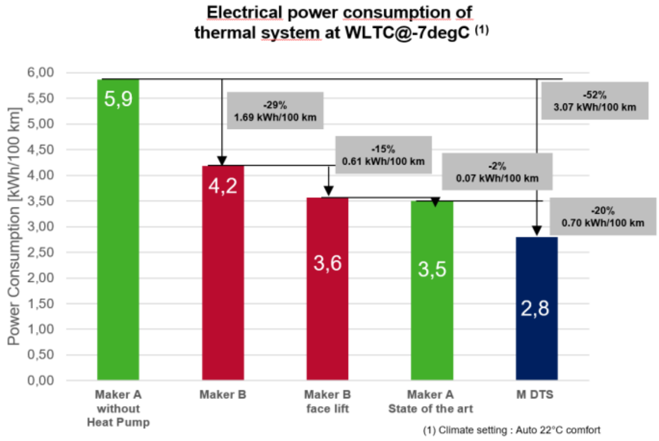

Figure 10. Energy consumption of BEV thermal system solutions [2] (Measurements in MAHLE vehicle wind tunnel)

ELECTRIC VEHICLE BATTERY

BEVs is largely considered from the automakers as a feasible solution for reaching the CO2 reduction legislations, and one of the most important and expensive components is the battery.

The battery is very much temperature sensitive. During the charge/discharge processes, the batteries start to generate heat due to its electrochemical reactions, and it is of extremely importance to have a control on the overall temperature of the battery cells, as well on the gradients among the cells. At high temperatures, the battery accelerates the aging due to overheating, reducing considerably its lifetime. And, at extreme temperature conditions, it can lead to a runaway, which is a chain of events causing organic solvents to break down and releasing gases, increasing pressure and temperature beyond its flashpoint causing the fire. At low temperatures, the overall power output of the battery reduces due to the decrease of its conductivity, affecting the battery´s performance. So, the battery has an 'comfortable' temperature working range, between 15°C and 40°C, where the thermal management system should guarantee in order its function and lifetime are not compromised [3].

Today´s most used technologies for battery cooling can be seen in the chart below (Figure 11).

The mainstream technology is the cooling plate, a thin layer where a coolant circuit is integrated into the plates to cool the battery cells that are placed in direct contact to its large surface plate.

At the lower end, there is the air-cooled technology with active blower, where the cells are cooled by air. This is mainly for lower cooling demand applications.

And at the higher end, there is the close to cell cooling technology, where the coolant is closer to the battery cells, in between or in all surrounding, for a more improved cooling performance.

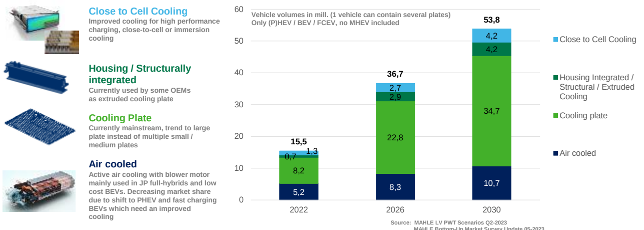

Figure 11. Battery Cooling Technologies and Market Growth [MAHLE]

BATTERY CHARGING – Beside the still existing driving range limitation compared to ICE vehicles, another important consumer acceptance barrier for electric vehicles is in the charging of the batteries. The infrastructure availability of the charging stations, the charging technology that is still under development, and the whole electric energy capacity grid situation, they all still have a way of development to go and to be at an ideal level. These topics will not be touched in this paper. But one important issue to be also solved, and has a lot to do with thermal management, is the charging time of BEVs battery. Compared to a standard ICE vehicle where the refueling at the gas stations only take few minutes, BEVs still take considerable time for the charging of the battery. Specially in long distance driving, this is an issue if consumers need to wait long time to be able to continue their journey.

During the charging time it is when the batteries most need an intensive temperature control. This is because the charging process creates chemical reactions that creates heat inside the cells, making the temperature to rise quickly. The role of a good thermal management system is to keep the cell temperature levels in the adequate level, to collect this heat to avoid cells overheating, and canalize this heat energy where the vehicle needs, for example, to the cabin heating.

The higher the charging power of a battery is, higher would be the heat rejection created, and as consequence, the needed cooling capacity to be provided. An insufficient battery cooling solution, in this way, can limit the charging speed potential.

As seen in the previous paragraphs, the current mainstream technology for battery cooling is the cooling plate solution. This solution supports battery charging power up to 250kW. For an average mid-size 80kWh BEV vehicle, it means approx. 20 minutes (10%-80% SOC) charging time. Already a good advance compared to a whole overnight charging time of first BEV models. But compared to an ICE vehicle refueling, it´s still a considerable difference the driver should wait in case there is an urgent need to continue the trip. Demand for more powerful charging power is already seen in premium segments, where the charging time is below 10 minutes. The charging power of battery in this condition is at 350kW level or higher. (Figure 12) High charging rate increase significantly the heat generated inside the battery. At this level, the cooling should be more effective and there is a need to the coolant come much closer to the battery cells. Close to cell or Immersion cooling technologies solutions are seen as new emerging technologies specially to fulfill sportscar and premium market vehicles.

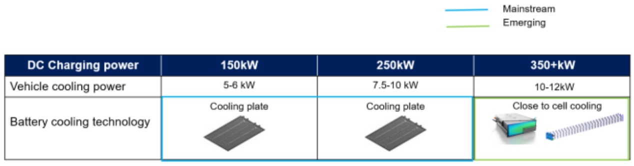

Figure 12. Battery cooling technology for charging [MAHLE]

<u>Cell Module with Immersion Cooling</u> – In the Immersion Cooling solution, the coolant has direct contact to the cell module and it flows around the cells. (Figure 13).

Different from the Cooling Plate solution, where the plate is in contact to only one of the sides of the battery cell, the Immersion Cooling solution guarantees homogeneous temperature profile in the cell, reducing efficiently the temperature gradient within the cell.

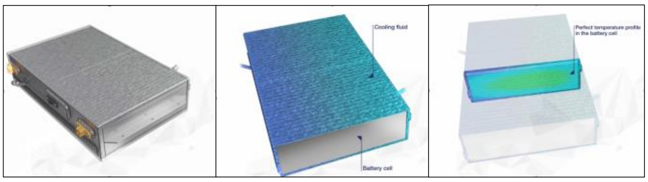

Figure 13. Immersion Cooling [MAHLE]

This is a scalable cell module solution for battery pack systems, allowing combinations of various cells modules to be expandable for bigger packs, suitable also for commercial vehicles application with megawatt charging possibility. Electrical connectors are also attention points when high charging power is involved. The heat generation in these connectors become very high, and the coolant need to be in direct contact to the terminal connections as well. So, no water-glycol coolant is applied, but instead, oil base dielectric fluid (non-conductive) is applied for increased safety. All these features allow the thermal management of the battery cells to be very effective, enabling reduced charging times at the charging points. (Figure 14)

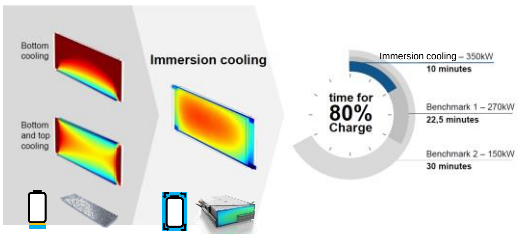

Figure 14. Battery cooling technology for charging [MAHLE]

THERMAL MANAGEMENT MODULES (TMM)

Electrification of a vehicle brings new function and components development demands to its supply chain.

In the first electrical vehicle generation, it was observed different solutions in terms of number of new components and its complexity. The cost of an electrical vehicle is still much higher than traditional ICE vehicle, and it remains as one of major barrier for wide adoption and acceptance BEVs in the market.

First EV generations thermal architecture includes multiple components and interfaces connected by different lines and hoses, that brings considerable complexity to the logistics and assembly efforts for the OEMs side. It also means high bill of material costs for the supplier side. For new generation EVs, solution of integrated thermal management modules is a key trend for components interfaces and overall assembly complexity reductions. (Figure 15)

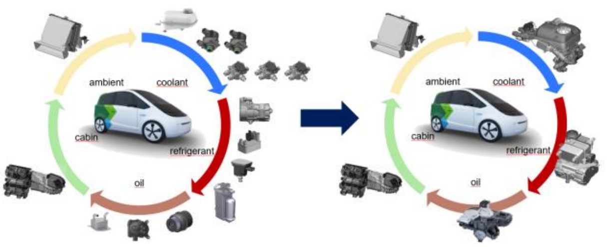

Figure 15. Modularization of thermal management components [MAHLE]

Thermal Management Modules solution has the following benefits:

- Significant reduction of vehicle interfaces and coolant or refrigerant lines
- Packaging and complexity reduction
- Reduced assembly effort for OEMs
- Compact module using inhouse developed and produced components

The modularization can be implemented in complex thermal circuits for coolant, refrigerant and oil circuits components. Example of application can be seen below. (Figure 16)

It reduces overall complexity of thermal circuits assembly in the vehicles and helps enabling more affordable electrical vehicles for end users.

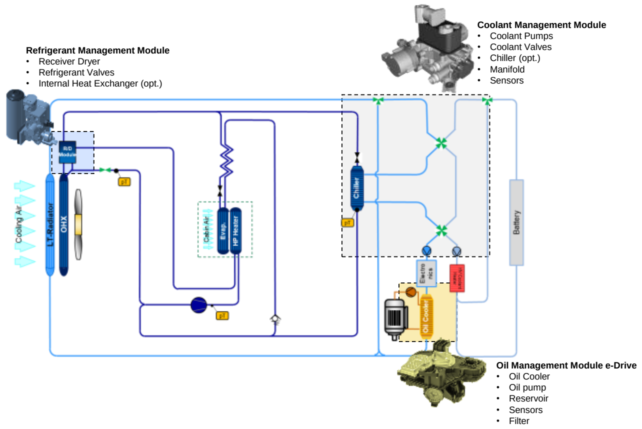

Figure 16. TMM - Thermal Management Modules in thermal circuits [MAHLE]

CONCLUSIONS

Already for some years, vehicle technology has been driven by the requirements of greenhouse gas emissions laws. The need of complete electrification of vehicles is creating a revolution in the global automotive industry, that is facing a huge challenge to convert their fleet from the traditional ICE technology to a new and still under development electrification technology.

ICE drive trains have been the main technology of the vehicles for decades, and even with the introduction of some electrical vehicles in the market, there are still some gaps to be filled in terms of usability and habits the drivers got used by the ICE standards along the years, like driving range mileage, fast battery charging time and vehicle affordability.

Examples of thermal management solutions were presented to technically support and enable the success of electrical vehicles.

As presented in the comparison measurements, the heat pump heater systems for the cabin heating, compared to the pure electrical heater solution, showed to be a good alternative since it improves the mileage reduction from the 40% found with the electrical heater solution, to only 27% reduction with the heat pump solution in a compact vehicle application. This represents an increase of 38,3% in absolute mileage numbers.

Benchmark comparison with internal vehicles measurements showed that with optimizations in the cooling circuit using the direct system (DTS) solution configuration, the electrical power consumption could be improved in 20% compared to the state-of-the-art market vehicle.

In the battery cooling technology, both the cooling plates and the immersion cooling technologies are supporting the potential of high charging rate of the batteries. This is an important factor to close the gap to traditional ICE users, that are used to have a few minutes refueling time at gas stations.

The challenge to deal with the complexity of multiple components and its interfaces can be simplified by the modularization of the sub-components and integration of their interfaces with the thermal management module solution. It avoids complex logistics and assembly efforts in the OEMs side, and the high number of components in the supplier side, supporting in this way to have more affordable electrical vehicles.

The transition to electrical vehicles is bringing to the whole industry a new perspective of product innovation and technology trend. The success of electrification in vehicles relies on some key factors, such as functionality, practicality, and cost reasonability. They should be minimally similar or superior to current standards so far set by ICE vehicles. And thermal energy management will remain as one of the key technologies for the success of electric vehicles due to the continuously limited level of available energy that future vehicles will face to meet requirements of the end user, and emission legislations.

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